

# An Automatic Invisible Axion In The SUSY Preon Model

**K.S. Babu<sup>a</sup>, Kiwoon Choi<sup>b</sup>, J.C. Pati<sup>c</sup> and X. Zhang<sup>d</sup>**

<sup>a</sup> Bartol Research Institute

University of Delaware, Newark, DE 19716

<sup>b</sup> Department of Physics

Korea Advanced Institute of Science and Technology

373-1 Kusong-dong, Yusong-gu, Taejon 305-701, Korea

<sup>c</sup> Department of Physics

University of Maryland, College Park, MD 20742

<sup>d</sup>Department of Physics

Iowa State University, Ames, IA 50011

## ABSTRACT

It is shown that the recently proposed preon model which provides a unified origin of the diverse mass scales and an explanation of family replication as well as of inter-family mass-hierarchy, naturally possesses a Peccei–Quinn (PQ) symmetry whose spontaneous breaking leads to an automatic invisible axion. Existence of the PQ-symmetry is simply a consequence of supersymmetry and the requirement of *minimality* in the field-content and interactions, which proposes that the lagrangian should possess only those terms which are dictated by the gauge principle and no others. In addition to the axion, the model also generates two superlight Goldstone bosons and their superpartners all of which are cosmologically safe.

1. The idea of the Peccei-Quinn (PQ) symmetry[1] provides one of the most elegant solutions to the strong CP problem, in that it forces  $\overline{\Theta}$ , determined to be  $\leq 10^{-9}$ , to vanish identically (barring negligible corrections from the electroweak sector). In practice, owing to constraints based on laboratory and astrophysical observations, the implementation of this idea requires a light invisible axion[2]. This in turn necessitates the scale of PQ symmetry breaking  $f_a$  to be rather high:  $10^{10}\text{GeV} \leq f_a \leq 10^{12}\text{GeV}$ [3].

There have been many suggestions in this regard, but invariably extra fields and/or the scale of PQ symmetry breaking have to be postulated from the beginning just to implement this idea[4]. For example, the idea of the composite axion, suggested by Kim [5,6], introduces new fermions together with a new axi-color force which seem to play no other role except implementing PQ symmetry and the invisible axion.

The purpose of this note is to point out that a composite invisible axion of the type envisaged in ref.[5,6] can naturally occur in the SUSY preon model[7] which has evolved over the last few years. The model exhibits several attractive features including an understanding of the origins of (i) diverse mass scales[7], (ii) protection of the masses of composite quarks and leptons compared to the scale of compositeness[8], (iii) family-replication[9] and (iv) inter-family mass-hierarchy[10]. The model also shows the possibility of a unification of forces at the level of preons near the Planck scale[11] and makes many testable predictions[12]. As we will show, the Peccei-Quinn symmetry emerges as an automatic feature of the model, stemming simply from the requirement of minimality in field content and interactions on which the model is built. This amounts to retaining only those terms in the lagrangian which have purely a gauge origin and no others. The fermions which make the composite invisible axion are the preons, which also make quarks,

leptons and Higgs bosons. In other words, they do not have to be postulated just to introduce the PQ symmetry. Furthermore, the PQ symmetry breaking scale is naturally identified in the model with the scale  $\Lambda_M$  of the preonic metacolor force, which represents the scale of compositeness. For several independent reasons, including (a) the observed mass of  $m_W$ [7] (b) the desired unity of forces[11] and (c) a desirable pattern for the neutrino masses[13],  $\Lambda_M$  is determined within the model to lie around  $10^{11}$  GeV, which is precisely within the allowed range of  $f_a$ .

**2.** To see the origin of the PQ symmetry and that of the invisible axion in the model, we need to present some of its salient features. The model[7] assumes that the effective lagrangian just below the Planck scale possesses  $N = 1$  local supersymmetry and a gauge symmetry of the form  $G_M \times G_{fc}$ . Here  $G_M = SU(N)_M$  (or  $SO(N)_M$ ) generates an asymptotically free metacolor gauge force which becomes strong at  $\Lambda_M \sim 10^{11}$  GeV and binds preons.  $G_{fc}$  denotes the flavor-color gauge symmetry, which is assumed to be either  $\mathcal{G}_{224} = SU(2)_L \times SU(2)_R \times SU(4)^c$ [14], or a subgroup of  $\mathcal{G}_{224}$  containing  $SU(2)_L \times U(1)_Y \times SU(3)^c$ . The gauge symmetry  $G_M \times G_{fc}$  operates on a set of six positive and six negative *massless* chiral preonic superfields  $\Phi_{\pm}^{a,\sigma} = (\varphi, \psi, F)_{L,R}^{a,\sigma}$ , each belonging to the fundamental representation  $N$  of  $SU(N)_M$ . Thus “a” runs over *six values*:  $(x, y); (r, y, b, \ell)$ , where  $(x, y)$  denote the two basic flavor-attributes  $(u, d)$  and  $(r, y, b, \ell)$  the four basic color-attributes of a quark-lepton family[14]. The index  $\sigma$  runs over metacolor quantum numbers. The representation content of the preonic superfields under the gauge symmetry is shown below:

	$SU(2)_L \times$	$SU(2)_R \times$	$SU(4)_{L+R}^C \times$	$SU(N)_{L+R}$
$\Phi_+^{f,\sigma} = (\varphi_L^f, \psi_L^f, F_L^f)^\sigma$	$\sim$	$2_L,$	$1,$	$1,$
$\Phi_-^{f,\sigma} = (\varphi_R^f, \psi_R^f, F_R^f)^\sigma$	$\sim$	$1,$	$2_R,$	$1,$
$\Phi_+^{c,\sigma} = (\varphi_L^c, \psi_L^c, F_L^c)^\sigma$	$\sim$	$1,$	$1,$	$4_c,$
$\Phi_-^{c,\sigma} = (\varphi_R^c, \psi_R^c, F_R^c)^\sigma$	$\sim$	$1,$	$1,$	$4_c,$

Here  $f$  stands for two preonic flavors  $\equiv (u, d)$ , while  $c$  denotes four colors ( $r, y, b$ , and  $\ell$ ). *Note that there is no repetition of any entity at the preon level.*

To be specific, we will assume that, just below the Planck scale, the gauge symmetry is  $G_{gauge} = SU(6)_M \times G_{fc}$  where  $G_{fc} = G_{224}$ , although our conclusion will not alter if  $G_{fc}$  is a subgroup of  $\mathcal{G}(2, 2, 4)$  containing the standard model[15].

In the interest of minimizing or removing all arbitrary parameters, the preon model[7] adheres to a principle of minimality, which proposes that the field content must be minimal, with no repetition of preonic entities, and so also must be the interactions. *Such a principle requires that the lagrangian should possess only those terms which are dictated by the gauge-covariant derivatives and no others.* This in particular permits no non-gauge mass, Yukawa and quartic couplings, which incidentally have been the main source of arbitrariness in the conventional approach to unification, based on fundamental Higgs bosons, quarks and leptons. By contrast, the preon model introduces no more than a few gauge couplings (e.g.  $\alpha_M$ ,  $\alpha_2$  and  $\alpha_4$ , defined near the Planck scale) as its *only parameters*. (Even these few gauge couplings would merge into one, if there is an underlying unity of forces at the preon-level, near the Planck scale[11]). Yet, it has been shown to be viable and capable of addressing some major issues[7-11].

The lagrangian of the preon model[7], restricted by such a principle, consists only of the minimal gauge interactions and possesses  $N = 1$  local SUSY. In other words, it has no  $F$ -term. Given six preonic attributes it is easy to verify that in the absence of the flavor-color gauge interactions (generated by  $G_{224}$ ), such a lagrangian would possess a global symmetry  $SU(6)_L \times SU(6)_R \times U(1)_V \times U(1)_X$ , while in their presence the global and local symmetry of the model, ignoring color

anomaly for a moment, is given by:

$$G_P = [U(1)_V \times U(1)_X \times U(1)_{T_L} \times U(1)_{T_R}]_{\text{(global)}} \\ \times [SU(6)_M \times SU(2)_L \times SU(2)_R \times SU(4)^c]_{\text{(local)}} \quad (1)$$

$U(1)_V$  and  $U(1)_X$  denote the preon-number and the non-anomalous R-symmetry respectively[16], which in our case assign the following charges to the preons:

$$Q_V(\Phi_{L,R}^{a,\alpha}) = 1; \quad Q_X(\varphi_{L,R}^{a,\alpha}) = 0 \\ Q_X(\Psi_L^{(a,\alpha)}) = -Q_X(\Psi_R^{(a,\alpha)}) = -Q_X(\lambda) = 1 \quad (2)$$

(Here the superspace Grassmann coordinate has  $N_X = 1$ .)  $T_{L,R}$  have the following representations in the space of  $(r, y, b, l, u, d)$ :

$$T_{L,R} = \text{diag.}(1, 1, 1, 1, -2, -2)_{L,R}. \quad (3)$$

It is useful to combine the four global  $U(1)$ 's listed in (1) as follows:

$$T_+ = T_L + T_R; \quad Q_V \\ Q_- = Q_X - (T_L - T_R); \quad Q_+ = Q_X + (T_L - T_R) . \quad (4)$$

Of the four global  $U(1)$ 's, only  $Q_{\pm}$  are chiral, among these only  $Q_+$  has a nonzero SU(3)-color anomaly and thus it is the one which serves as the Peccei-Quinn charge.

We stress that the existence of the four global  $U(1)$  symmetries including  $U(1)_X$ , and thus of the PQ symmetry  $Q_+$ , is a natural feature of the model, in the sense that they emerge simply from the assumption of minimality in field content and interactions[17]. We now discuss spontaneous breaking of some or all of these symmetries.

**3. Symmetry Breaking**: It is assumed that as the asymptotically free meta-color force becomes strong at a scale  $\Lambda_M \sim 10^{11} \text{ GeV}$ , (a) it confines preons to

make composite quarks and leptons, and (b) it forms a few SUSY-preserving and also SUSY-breaking condensates, all of which preserve metacolor. The latter include the metagaugino pair  $\langle \vec{\lambda} \cdot \vec{\lambda} \rangle$  and the preonic fermion-pairs  $\langle \bar{\psi}^a \psi^a \rangle$ , both of which break SUSY in a massless preon theory. Noting that in the model under consideration, a dynamical breaking of SUSY would be forbidden owing to the Witten-index theorem[18], it has been argued[8] that each of these fermionic condensates, which do break SUSY, must be damped by  $(\Lambda_M/M_{Pl})$ , so that each would vanish in the absence of gravity (i.e., as  $M_{Pl} \rightarrow \infty$ ). We thus expect[8,7]:

$$\langle \bar{\psi}^a \psi^a \rangle = a_{\psi_a} \Lambda_M^3 (\Lambda_M/M_{Pl}); \quad \langle \vec{\lambda} \cdot \vec{\lambda} \rangle = a_\lambda \Lambda_M^3 (\Lambda_M/M_{Pl}) \quad (5)$$

where  $a_{\psi_a}$  and  $a_\lambda$  are apriori expected to be of order unity. These induce SUSY-breaking mass-splittings  $\delta m_S \sim \Lambda_M (\Lambda_M/M_{Pl}) \sim 1 \text{ TeV}$ . In addition,  $\langle \bar{\psi}^a \psi^a \rangle$ -condensates break  $SU(2) \times U(1)$  for  $a = (x, y)$  and give masses to  $W$  and  $Z$  of order  $(1/10)\Lambda_M (\Lambda_M/M_{Pl}) \sim 100 \text{ GeV}$ , as well as to quarks and leptons which are  $\leq 100 \text{ GeV}$ [7,10].

The SUSY-preserving condensates have no reason to be suppressed. They are thus expected to be of order  $\Lambda_M \sim 10^{11} \text{ GeV}$ . Although, in principle, the pattern of condensates which form, should be derivable from the underlying preonic theory, in practice, one is far from being able to do so. This is because of our inexperience in dealing with the non-perturbative dynamics of SUSY QCD (leaving aside, of course, some general results like the index theorem[18]). The preonic idea seems most attractive and thus worth pursuing, nevertheless, because of its utmost economy in parameters. With this in view, we proceed by making a *broad dynamical assumption* which is this: (a) SUSY QCD (with  $m_\psi^{(0)} = m_\phi^{(0)} = 0$ ), unrestricted by the constraints of the Vafa-Witten theorem[19], permits a dynamical breaking of parity and vectorial symmetries like “isospin” ( $SU(2)_{L+R}$ ), baryon and/or lepton numbers; (b) A suitable set of metacolor-singlet, SUSY-preserving, condensates

form, which break the gauge symmetry  $SU(2)_L \times SU(2)_R \times SU(4)^c$  into the standard model symmetry  $SU(2)_L \times U(1)_Y \times SU(3)^c$ , and simultaneously also all or at least a major subset of the global  $U(1)$ 's listed in (1), at the scale  $\Lambda_M$ [20]. To be specific, it is assumed that the SUSY-preserving metacolor singlet condensates (written in a schematic notation) include:

$$\begin{aligned}
<\Delta_R> &= <\psi_R^{u\alpha} \psi_R^{u\beta} \phi_{L\alpha}^{l*} \phi_{L\beta}^{l*}> \sim (1, 3_R, 10^c) \\
< S_R > &= <\phi_R^{u\alpha} \phi_R^{u\beta} \phi_{L\alpha}^{l*} \phi_{L\beta}^{l*}> \sim (1, 3_R, 10^c) \\
<\xi_1> &= <\epsilon_{\alpha\beta\gamma\delta\rho\sigma} \phi_R^{r\alpha} \phi_R^{y\beta} \phi_R^{b\gamma} \phi_R^{l\delta} \phi_R^{u\rho} \phi_R^{d\sigma}> \sim (1, 1, 1^c) \\
<\xi_2> &= <\epsilon_{\alpha\beta\gamma\delta\rho\sigma} \phi_R^{r\alpha} \phi_R^{y\beta} \phi_R^{b\gamma} \phi_R^{l\delta} \phi_L^{u\rho} \phi_L^{d\sigma}> \sim (1, 1, 1^c) .
\end{aligned} \tag{6}$$

The transformation property of the full-multiplet, containing the condensate, under  $SU(2)_L \times SU(2)_R \times SU(4)^c$  is exhibited on the right. Antisymmetrisation on the  $SU(3)^c$ -indices is to be understood. While the formation of these condensates is a dynamical assumption of the model[20], it may be noted that each of these condensates is at least in a highly attractive channel. For example,  $\Delta_R$  involves  $(\psi\phi^*)_{Adjoint}$   $(\psi\phi^*)_{Adjoint}$  and  $S_R$  involves  $(\phi\phi^*)_{Adjoint}$   $(\phi\phi^*)_{Adjoint}$  combinations. Unlike  $<\bar{\psi}\psi>$  and  $<\lambda\lambda>$ , these condensates can form, while preserving SUSY. Their quantum numbers are listed below:

	$B - L$	$I_{3R}$	$Q_V$	$Q_X$	$T_L$	$T_R$
$<\Delta_R>$	-2	1	0	-2	-2	-4
$< S_R >$	-2	1	0	0	-2	-4
$<\xi_1>$	0	0	6	0	0	0
$<\xi_2>$	0	0	6	0	-4	4

It is then easy to see that the condensates of eq. (6) break the symmetry group  $G$  (see eq. (1)) down to

$$SU(2)_L \times U(1)_Y \times SU(3)^c \times [U(1)_H]_{global}, \tag{8}$$

where  $Y = I_{3R} + (B - L)/2$  is the weak hypercharge and the charge for  $U(1)_H$ , in the space of the preon-flavors  $(r, y, b, l, u, d)_{L,R}$ , is given by

$$\begin{aligned} Q_H &= T_L + T_R - 3(B - L) \\ &= \text{diag.}(2, 2, 2, -2, -2, -2)_{L,R} \end{aligned} \tag{9}$$

The charge  $Q_H$  is vectorial and acts effectively as baryon number, because

$$Q_H(\text{quarks } \sim \psi_u \varphi_r^*) = -4; \quad Q_H(\text{leptons } \sim \psi_u \varphi_l^*) = 0. \tag{10}$$

If  $Q_H$  is preserved, proton will be stable. It is possible that  $Q_H$  breaks through additional condensates so as to induce proton decay (see remarks later). Even without such condensates,  $Q_H$  breaks through  $SU(2)_L$ -anomaly, however the proton decay induced by  $SU(2)_L$ -instantons would be too slow to be observable, as observed by 't Hooft[21].

#### 4. *Supermultiplets of axion and other Goldstone bosons:*

As mentioned above, of the four global  $U(1)$  symmetries listed in (4), only the combination  $Q_H = T_L + T_R - 3(B - L)$  is preserved, while the remaining three –i.e.,  $Q_V$ ,  $Q_-$  and  $Q_+$  – are broken spontaneously at  $\Lambda_M$  by the condensates listed in (6). Such a breaking thus generates *three physical Goldstone bosons* each with a decay constant of the order of  $\Lambda_M$ .

Of the three spontaneously broken global  $U(1)$ 's,  $Q_V$  and  $Q_-$  are broken explicitly by  $SU(2)_L$  anomaly, while  $Q_+$  is broken by both QCD and  $SU(2)_L$  anomalies. Thus  $Q_+$  can be identified as a PQ symmetry. Its existence provides the familiar resolution of the strong–CP problem[1], and its spontaneous breaking at  $\Lambda_M$  generates the standard invisible axion (see below).

We now observe that although  $Q_V$  and  $Q_H$  are broken explicitly by  $SU(2)_L$  anomalies, the linear combination  $Q'_V \equiv (2Q_V + Q_H) = \text{diag.}(4, 4, 4, 0, 0, 0)_{L,R}$  is free from anomalies. We therefore expect that there will be one *exactly massless* Goldstone boson associated with the spontaneous breaking of  $Q'_V$ . For this reason, we will discuss the Goldstone boson spectrum in terms of  $Q_+, Q_-$  and  $Q'_V$ .

We denote the Goldstone bosons corresponding to spontaneous breaking of  $Q_+, Q_-$  and  $Q'_V$  by  $a_+, a_-$  and  $a_V$  respectively, which are named as follows:

$$(Q_+, Q_-, Q'_V) \rightarrow \{\text{axion}(a_+), \text{chion}(a_-), \text{vion}(a_V)\} \quad (11)$$

Let “ $\phi_i$ ” denote these three Goldstone bosons. At energy scales well below  $\Lambda_M$ , the effective interactions of  $\phi_i$  can be written as

$$\frac{1}{\Lambda_M} \partial_\mu \phi_i J_i^\mu + \frac{1}{16\pi^2} \frac{\phi_i}{\Lambda_M} (c_i G \tilde{G} + d_i W \tilde{W}), \quad (12)$$

where  $J_i^\mu$  denotes the appropriate current mode of generic composite fields, e.g. quarks and leptons, with masses far below  $\Lambda_M$ ,  $G$  and  $W$  are the gluon and  $W$ -boson field strengths respectively, and  $\tilde{G}$  and  $\tilde{W}$  are their duals. The coefficients  $c_i$  and  $d_i$  are in general of order unity, except for  $Q'_V$ , for which  $c = d = 0$ .

The axion coupling to QCD anomaly generates an axion mass

$m_a \sim f_\pi m_\pi / \Lambda_M \sim 10^{-4} \text{ eV}$ , with  $\Lambda_M \sim 10^{11} \text{ GeV}$ . This is the invisible axion, which is a leading candidate for cold dark matter. As is well known, for  $\Lambda_M \sim 10^{11} \text{ GeV}$ , axions and other Goldstone bosons, with the coupling of eq. (12) are consistent with all phenomenological constraints including those arising from astrophysical and cosmological arguments.

As for the other two Goldstone bosons – chion ( $a_-$ ) and vion ( $a_V$ ) –  $SU(2)_L$ -instantons induce a mass for  $a_-$ , but not for  $a_V$ , since  $Q'_V$  has no  $SU(2)_L$  anomaly. Suppressed by the  $SU(2)_L$ -instanton factor and also the small neutrino masses, the mass of  $a_-$  is expected to be lighter than  $(v_{EW}/\Lambda_M)^{1/2} (v_{EW}) e^{-4\pi^2/g_2^2} \sim 10^{-34} \text{ eV}$ . If it exists, chion may well be the *lightest massive particle* of nature. Because of its coupling to  $W \tilde{W}$  (see eq. (12)), it would decay into two photons with a lifetime far exceeding the age of the universe. The vion, on the other hand, is exactly massless and stable. Such ultralight and very weakly interacting objects would, of course, have no cosmological significance, unlike the axion.

Because of supersymmetry, the Goldstone bosons ( $a_i$ ),  $i = +, -, V$  will be accompanied by spin-1/2 partners  $\tilde{a}_i$  and real spin-0 scalar partners  $s_i$ , which form the Goldstone supermultiplets:  $A_i = (s_i + ia_i, \tilde{a}_i, F_i)$ . These superpartners corresponding to  $i = +, -, V$  may be named as: (saxion ( $s_+$ ), axino ( $\tilde{a}_+$ )); (schion ( $s_-$ ), chino ( $\tilde{a}_-$ )); and (svion ( $s_V$ ), vino ( $\tilde{a}_V$ )).

The couplings of  $s_i$  and  $\tilde{a}_i$  may be obtained from the supersymmetrized form of (12) which is given by

$$\frac{k_{ij}}{\Lambda_M} [(A + \bar{A}) \bar{Z}_j Z_j]_D + \frac{1}{16\pi^2} \left[ \frac{A_i}{\Lambda_M} (c_i W_G W_G + d_i W_W W_W) \right]_F + \text{h.c.} \quad (13)$$

Here  $Z_j = (z_j, \chi_j, F_j)$  denote composite chiral matter superfields including those of quarks and leptons whose possible gauge interactions are ignored here,  $W_G$  and  $W_W$  are the gauge-covariant chiral gauge superfields for  $SU(3)^c$  and  $SU(2)_L$  respectively, and the subscripts  $F$  and  $D$  stand for the  $F$  and  $D$ -components of superfields. The coefficients  $k_{ij}$  would depend upon the details of metacolor dynamics, but are expected to be of order unity in general since they are *not* forbidden by any of the unbroken symmetries.

Clearly the low energy couplings of all three pairs of superpartners – i.e., (axino, saxion), (chino, schion) and (vino, svion) – to normal matter are suppressed by  $1/\Lambda_M$  as those of the axion. Although these superpartners will not lead to any significant consequences for accelerator experiments, since  $\Lambda_M \sim 10^{11}$  GeV, they may play some role in cosmology. In the SUSY preon model, it is expected that each of these superpartners have masses of  $10^2 - 10^3$  GeV, which is the effective SUSY-breaking scale. Then the effective interactions of eq. (13), which would allow coupling of the form  $\tilde{a}_i \rightarrow \tilde{W}_{1/2} W$  and  $s_i \rightarrow W^+ W^-$ , would provide a variety of decay channels of these pairs: e.g.  $\tilde{a}_i \rightarrow z_j \chi_j, \gamma \tilde{\gamma}$ , and  $s_i \rightarrow \chi_j \bar{\chi}_j, \gamma \gamma$ , and possibly also  $\tilde{a}_i \rightarrow W \tilde{W}_{1/2}$  and  $s_i \rightarrow WW$  (if  $\tilde{a}_i$  and  $s_i$  are massive enough). The possible decay modes and the corresponding life times  $\tau(\tilde{a}_i, s_i)$  depend on

the details of the mass spectrum and also the mixings among involved particles. With their masses around  $10^2 \sim 10^3$  GeV (and  $\Lambda_M \sim 10^{11}$  GeV), we estimate that  $\tau(\tilde{a}_i, s_i) \ll 1$  sec. This is cosmologically safe.

It is worth noting that the effective coupling of the light Goldstone bosons with the  $SU(2)_L$  gauge bosons, induced by anomaly, would in turn lead to their couplings with fermion-pairs, whose strengths would be of order  $\alpha_W^2 m_f / \Lambda_M$ ; where  $m_f$  is the mass of the relevant fermion. Since the energy loss in red giants puts a constraint on the coupling of any such light particle to  $e\bar{e}$  pair to be less than  $10^{-13}$ [3], it follows that  $\Lambda_M \geq 10^6$  GeV. This, of course, is satisfied in the preon model, since  $\Lambda_M \sim 10^{11}$  GeV.

Before closing, a few comments are in order: (1) First, we have checked that our scheme of spontaneous symmetry breaking yields three disconnected degenerate vacua, and thus results in domain walls. One would then need inflation to resolve the domain wall problem. Inflation is, of course, needed in any model to resolve other cosmological issues, in particular the horizon and the flatness problems. The possibility of generating a satisfactory potential for implementing the “new” inflation scenario in a SUSY preon model, because of SUSY-forbiddenness of certain mass and coupling parameters, has been considered elsewhere[22].

(2) Although the discussions in this paper are based on a specific set of condensates (eq. (6)), our conclusion about the existence of an invisible axion is more general. In fact, any alternative set of condensates which breaks the preonic symmetry  $G_P$  to the standard model gauge symmetry at  $\Lambda_M$  will automatically yield the standard invisible axion. This is because  $\Lambda_M$  is determined within the model on *other grounds* to be about  $10^{11}$  GeV.

(3) Third, we note in passing that the condensate pattern listed in (6) violates lepton number and gives a Majorana mass to the right-handed neutrinos, but it

conserves  $Q_H$  and thus leaves proton stable. Baryon non-conservation and proton decay would, however, occur at an observable rate if two additional condensates such as  $\langle \Sigma \rangle \propto \langle \psi_L^u \psi_L^d \psi_R^u \psi_R^d \varphi_L^u \varphi_L^d \rangle$  and  $\langle \zeta \rangle \propto \langle \varphi_L^r \varphi_L^y \varphi_L^b \varphi_L^l \varphi_L^u \varphi_L^d \rangle$ , which preserve  $SU(6)_M$  and  $SU(2)_L \times SU(2)_R \times SU(4)^c$ , form. One can argue that  $\langle \Sigma \rangle$  breaks SUSY while  $\langle \zeta \rangle$  preserves SUSY. Thus, following Ref. 8, one would expect that  $\langle \Sigma \rangle \sim \Lambda_M (\Lambda_M/M_{Pl})$  and  $\langle \zeta \rangle \sim \Lambda_M$ . This leads to an amplitude for  $(3q \rightarrow \bar{l})$  of order  $(\Lambda_M/M_{Pl})/\Lambda_M^2 \sim 10^{-8} \times 10^{-22} \text{ GeV}^{-2} \sim 10^{-30} \text{ GeV}^{-2}$ . Remarkably enough, this is *precisely* the right order of magnitude for proton to decay into  $e^+ \pi^0$  with lifetime  $\sim 10^{32} - 10^{33}$  yrs. This point will be considered in more detail elsewhere.

To conclude, we see that the preon model, subject to the assumption of minimality in field content and interactions automatically possesses a PQ symmetry. Subject to a broad dynamical assumption about the pattern of symmetry breaking, it leads naturally to an invisible axion because the symmetry breaking scale  $\Lambda_M$  is determined on *other grounds* to be about  $10^{11} \text{ GeV}$ . The model also generates one massless and one superlight Goldstone boson with mass  $\leq 10^{-34} \text{ eV}$  as well as the spin-0 and spin-1/2 superpartners of all three Goldstone bosons with masses of the order of  $10^2 - 10^3 \text{ GeV}$ . All of these particles are cosmologically safe, either because they are superlight and very weakly coupled or because they are sufficiently short-lived. Meanwhile the axion serves as a strong candidate for cold dark matter.

**Acknowledgement** The research of K.S.B is supported in part by a grant from the Department of Energy. X.Z is supported in part by the Office of High Energy and Nuclear Physics of the U.S. Department of Energy (Grant No. DE-FG02-94ER40817). J.C.P is supported in part by a grant from the National Science Foundation. The work of K. Choi is supported in part by KOSEF through the CTP

at Seoul National University. K. Choi and J. C. Pati acknowledge the hospitality of the ICTP, Trieste where part of this work was done. JCP wishes to thank Michael Dine, Andre Linde and Helen Quinn for helpful discussions.

### References

- [1] R.D. Peccei and H. Quinn, Phys. Rev. Lett. **38**, 1440 (1977).
- [2] J.E. Kim, Phys. Rev. Lett. **43**, 103 (1979); M.A. Shifman, A.I. Vainshtein and V.I. Zakharov, Nucl. Phys. **B166**, 199 (1981); M. Dine, W. Fischler and M. Srednicki, Phys. Lett. **B104**, 199 (1981); A.P. Zhitniskii, Sov. J. Nucl. Phys. **31**, 260 (1980).
- [3] For a review see, J.E. Kim, Phys. Rept. **149**, 1 (1987); M. S. Turner, Phys. Rep. **197**, 67 (1990); G. G. Raffelt, Phys. Rep. **198**, 1 (1990).
- [4] For some notable exceptions, see e.g. P. Langacker, R. Peccei and T. Yanagida, Mod. Phys. Lett. **1**, 541 (1986); K. Kang and M. Shin, *ibid.*, **1**, 585 (1986); D. Chang and G. Senjanovic, Phys. Lett. **B188**, 231 (1987); G. Lazarides, C. Panagiotakopoulos and Q. Shafi, Phys. Rev. Lett. **56**, 432 (1986).
- [5] J.E. Kim, Phys. Rev. **D 31**, 1733 (1985).
- [6] K. Choi and J. E. Kim, Phys. Rev. **D 32**, 1828 (1985).
- [7] J.C. Pati, Phys. Lett. **B228**, 228 (1989); For a recent review, see J.C. Pati, “Towards a Pure Gauge origin of the Fundamental Forces: Unity through Preons”, UMD Publication 94-069, Proceedings SUSY Conf. held at Boston, ed. by P. Nath, (World Scientific) page 255.
- [8] J.C. Pati, M. Cvetic and H. Sharatchandra, Phys. Rev. Lett. **58**, 851 (1987).
- [9] K.S. Babu, J.C. Pati and H. Stremnitzer, Phys. Lett. **B256**, 206 (1991).
- [10] K.S. Babu, J.C. Pati and H. Stremnitzer, Phys. Rev. Lett. **67**, 1688 (1991).
- [11] K.S. Babu and J.C. Pati, Phys. Rev. **D 48**, R1921 (1993).
- [12] See ref.[7,10] and K.S. Babu, J.C. Pati and X. Zhang, Phys. Rev. **D 46**, 2190

(1992).

- [13] K.S. Babu, J.C. Pati and H. Stremnitzer, Phys. Lett. **B264**, 347 (1991).
- [14] J.C. Pati and A. Salam, Phys. Rev. Lett. **31**, 661 (1973); Phys. Rev. **D10**, 275 (1974).
- [15] Although much of our results is not tied to a precise choice of  $G_M$ , the choice  $G_M = SU(6)$  seems to be suggested by the following set of considerations: (i) the desire to achieve unification[11], which suggests that, if  $G_M = SU(N)$ ,  $N$  should not be smaller than 4 and larger than 6; (ii) the need to avoid Witten  $SU(2)$ -anomaly which says that  $N$  should be even and (iii) the fact that we utilize the Witten index theorem and that the index has been calculated and found to be non-zero for the case of massless preons only when the number of preon flavors which is six, is an integer multiple of the “number” of metacolor  $N$  (see the last paper in Ref. 18).
- [16] I. Affleck, M. Dine and N. Seiberg, Nucl. Phys. **241B**, 493 (1984); Nucl. Phys. **256B**, 557 (1985). Note that in our case, the number of preon flavors is equal to the number of metacolors, both of which are six. As discussed in the reference mentioned above, in this case, the instantons do not contribute to the superpotential and thus do not help choose between  $\varphi_{L,R} = 0$  (confining solution) and  $\varphi_{L,R} \rightarrow \infty$  (Higgs mode). Thus, at least there is no general argument preventing the SUSY preon theory from becoming strongly interacting and confining, while preserving the metacolor gauge symmetry corresponding to  $\varphi_{L,R} = 0$  (see Ref. 8 for further discussions).
- [17] We note that if one did not insist on the principle of minimality, one could, of course, have introduced arbitrary mass terms for the color-carrying preons by allowing terms such as  $m\Phi_+^c\Phi_-^{c*}$  in the superpotential, which would be gauge-invariant, but which would not respect  $U(1)_X$ ,  $T_L$  and  $T_R$ . Thus it is

the minimality in the interactions which ensures the symmetries  $U(1)_X, T_L$  and  $T_R$ . Conversely, if one imposes  $U(1)_X$  in addition to gauge invariance and supersymmetry, *no* non-gauge terms (i.e., no  $F$ -term) would be allowed and minimality would follow (see also remarks in Ref. 17). We are aware that Planck scale effects involving quantum black hole and/or worm hole effects could in general erase global symmetries like  $U(1)_X$  and thus need not respect the principle of minimality. (See eg. T. Banks, *Physicalia*, **12**, 19 (1990); J. Preskill, *Proceedings of the Int. Symp. of Gravity*, the Woodlands, Texas (1992).) Since the analysis of these effects, based on euclidian metric and not well-understood quantum gravity, is still not conclusive, at least in so far as the magnitude of these effects, we ignore their implications for the present. It is conceivable that one would find additional reasons to either forbid or suppress sufficiently the unwanted Planck-scale effects anyhow.

- [18] E. Witten, *Nucl. Phys.* **B 202**, 253 (1982); S. Cecotti and L. Giradello, *Phys. Lett.* **B110**, 39 (1983); E. Cohen and L. Gomez, *Phys. Rev. Lett.* **52**, 237 (1984).
- [19] C. Vafa and E. Witten, *Phys. Rev. Lett.* **53**, 535 (1984) and *Nucl. Phys.* **B234**, 173 (1984).
- [20] To draw a perspective, while the assumed pattern of symmetry breaking is not altogether implausible in that the needed condensates are in highly attractive channels, the choice in this regard is nevertheless arbitrary. This represents a negative element in the preonic approach. On the positive side, while the pattern of condensates needs to be assumed, the scales of the condensates including those with a damping by  $(\Lambda_M/M_{Pl})$  are motivated on general grounds. Furthermore, corresponding to the broad assumption about the pattern of symmetry breaking, the preon model makes a *host of predictions*.

tions[7,9,10,12], on the basis of which the said assumptions can be amply tested. It also explains the inter–family mass–hierarchy and the hierarchy of scales from  $M_{Pl}$  to  $m_\nu$ . These are among the main reasons why one feels “justified” to pursue the preon model, in spite of the needed dynamical assumption about the pattern of symmetry breaking. For what it is worth, we remark in passing that a certain arbitrariness, stemming from ignorance in dynamics, is not exclusive to the preon theory, but is present in more ambitious approaches as well. Compare e.g. the needed VEVs of the scalar  $\nu_R$  and  $N$  in the three–generation Calabi–Yau models, or for that matter the needed assumption that higher dimensional superstring theories compactify into four dimensions. For the elementary Higgs–picture, there is, of course, the complete arbitrariness in the choice of representations of the Higgs multiplets and the associated parameters, and thereby in the pattern of VEVs. The preon model has the relative merit, as mentioned above, that at least it makes certain crucial predictions, by which it can be excluded, if it is wrong, or confirmed, if it is right.

- [21] G. 't Hooft, in *Recent Developments in Gauge Theories*, eds. G. 't Hooft et. al., (Plenum, NY 1980), p. 135.
- [22] M. Cvetic, T. Hubsch, J.C. Pati and H. Stremnitzer, Phys. Rev. **D 40**, 1311 (1989).